
Reservoir EFFICIENCY Processes Program

*Research to
Improve Recovery
of Oil & Gas*



OIL AND GAS RD&D PROGRAMS

RESERVOIR
EFFICIENCY

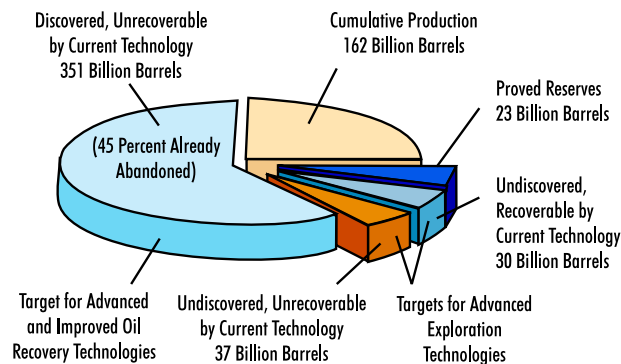
To the uninitiated, efficient oil recovery is far more difficult than it appears. It is a cliché to say that, of the discovered oil in the ground, only one-third is typically recovered; but the statement bears repeating for its profound implications. In fact, average oil recovery from U.S. reservoirs is about 32 percent. Although it is physically impossible to recover all of the oil that is discovered, the potential for improvement with the use of technology is very large indeed.

Today, the United States is considered a mature oil and gas province. Production of easily-accessible oil peaked in 1970 and has declined since then. Advanced technologies, often based on sophisticated computer modeling, hold great promise for additional oil and gas production from the Nation's remaining hydrocarbon resources. Using tomorrow's advanced technologies, our Nation will be able to slow down,

even stabilize, the currently declining oil production rate and increase the gas production rate. More importantly, it is imperative that we reduce the rate at which domestic oil and gas fields are being abandoned. Once shut-in or abandoned, oil and gas reservoirs cannot be economically restored to the production status due to the high costs associated with developing the field.

The U.S. Department of Energy, in partnership with the oil and gas industry, academia, and the National Laboratories, supports basic and applied research of physical and chemical processes that govern fluid flow in porous media. This combination of the best public and private research capabilities has already produced remarkable results. Our goal is to accelerate the creation and implementation of promising, innovative approaches to increase recovery efficiency processes.

Original Oil in Place: 603 Billion Barrels



Reservoir Efficiency Processes Program

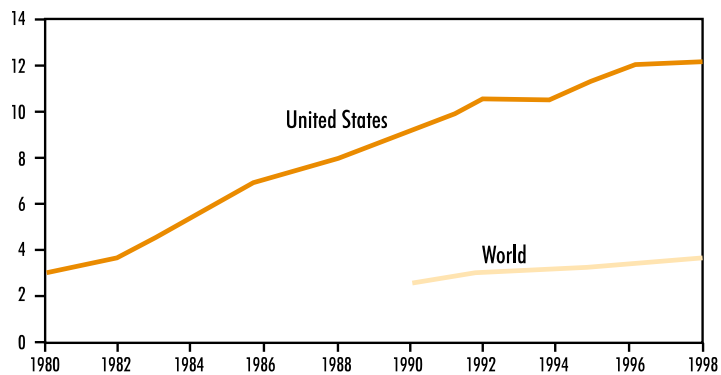
Despite the maturing of the United States as an oil producing region, the oil industry remains an important source of capital formation, technology development, and employment in our economy. Industry relies on advanced technology, in which American companies have been world leaders and the driving force in technical innovations.

Many mature U.S. oil fields face imminent abandonment as they approach their economic limit. The Reservoir Efficiency Processes Program addresses all aspects of upstream petroleum research, but focuses on improved, less expensive, and less risky oil recovery technologies. These technologies are known as enhanced oil recovery (EOR) processes. In general, EOR technologies fall into one of the following four categories: thermal, gas-miscible and -immiscible, chemical, and microbial. New or improved technologies often combine elements from more than one category. Methods of the future include unconventional approaches, such as field-wide development of strategically-placed horizontal wells, gravity drainage enhancement, microbial EOR, and radio frequency heating.

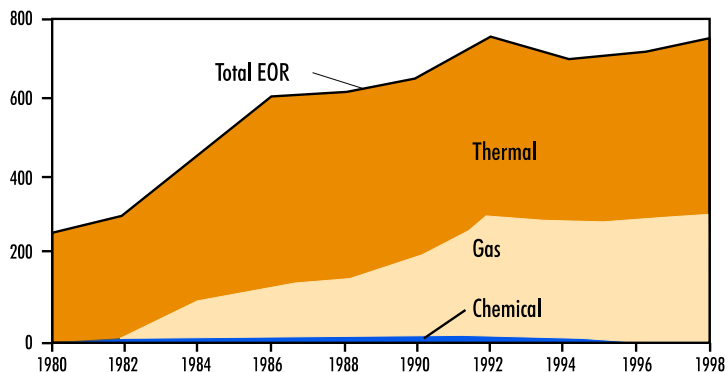
The U.S. leads the world in EOR technology. Already, 12 percent of U.S. oil production is from EOR applications, and that fraction is growing steadily. The world's EOR production is about three percent and also growing.

Enhanced Oil Recovery

Application of EOR processing has been increasing both in the U.S. and the world. At present, EOR methods contribute 725,000 barrels per day to U.S. oil production – 12 percent of total oil produced. The specific contribution of gas-miscible projects using carbon dioxide continues to grow.



Growth of EOR in the United States and the World



EOR Production in the U.S. by Major Recovery Technology

Government Role

Without a first-class research, we can only look forward to second-class economy and a second-class standard of living. Our currently high standard of living is in large part due to the plentiful and inexpensive supply of energy in the form of oil and gas. However, the petroleum industry's funding for R&D has been decreasing. The independent sector of the industry conducts practically no research, yet the independents produce from mature fields that need research to maximize their production. These mature domestic oil and gas fields are in danger of premature abandonment without new production technologies from government-supported research.

The need for Federal support of research on reservoir efficiency processes arises, in part, from the Federal ownership of lands that contain oil and gas, which provide royalty revenues to the Treasury. Efficient management and optimal development of Federal lands is in the national interest.

No less important is the continuing and steady decline of oil production in the U.S. and the steadily increasing abandonments of oil and gas wells caused by their insufficient productivity. Abandoned wells can create environmentally-sensitive disposal

problems (in itself a Federal and a State role), and preclude reservoir access, even if the economics and technology improve sufficiently to warrant their reopening. Proper abandonment requires plugging wells with cement, such that they cannot be redrilled economically. On the average, this leaves approximately one-half of the residual oil and about one-third of natural gas to be unrecoverable – a major loss of national resources. This problem requires urgent national attention.

The Federal Government has access to the unique capabilities of National Laboratories that were acquired from defense programs with public funds. Many of these capabilities, such as the numerical modeling and super computing power of the newest hardware, are required for solving exceedingly complex problems encountered in reservoir simulation. The government can easily adapt these technologies to increase the competitiveness of the U.S. petroleum industry. Direct participation of the industry assures rapid and effective technology transfer under existing successful programs, such as the Natural Gas and Oil Technology Partnership, and the Petroleum Technology Transfer Council (PTTC).

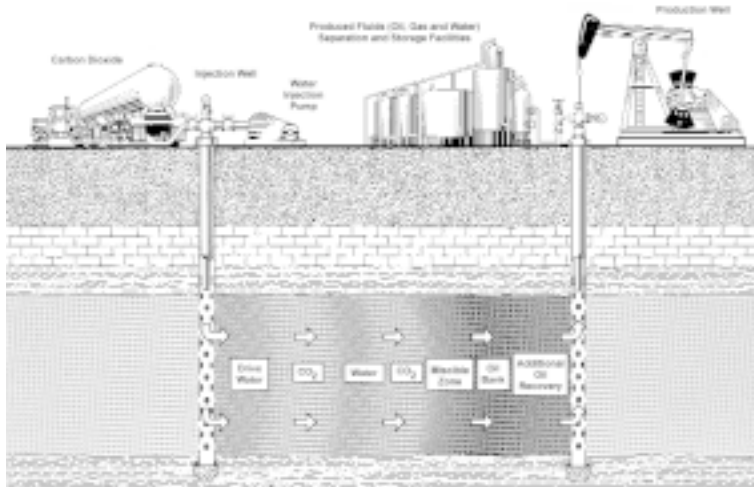
The Need for Research in Reservoir Efficiency Processes

Changes in technology, competition, resource base, and politics have transformed the petroleum industry. Some of the most significant changes include:

- The decline of U.S. oil production and reserves since 1970, with decreased hope for the reversal of this trend.
- Increase of oil and gas well abandonments, due to insufficient productivity and low oil prices. Once abandoned, redevelopment cannot be justified and future access to reservoirs is foreclosed, even with improved technologies.
- Concern for improving the environment has led to new regulations imposed on industry by State and Federal agencies, which add costs to operations. This particularly affects the independent producers operating marginal wells. Increasing cost of complying with regulations is often the reason for many companies to move overseas.
- Downsizing in the petroleum industry and reduction of basic and applied research. Independents, in particular, drill 85 percent of all U.S. wells, produce 66 percent of natural gas and 40 percent of crude oil, but do not conduct their own research.
- As a consequence, more than 15,000 to 22,000 marginal oil and gas wells are abandoned every year, and about 220,000 wells are idled (not producing).

Use of advanced technology enables reduced production costs during times of depressed prices. Advanced technology can uniquely access the already discovered but unrecovered resource; on average, two-thirds of the discovered resource is currently unrecoverable.

RESERVOIR
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CARBON DIOXIDE FLOODING

This method is a miscible displacement process applicable to many reservoirs. A carbon dioxide slug followed by alternate water and carbon dioxide injections is usually the most feasible method.

Key Enhanced Oil Recovery Methods

Thermal Recovery

Steam Injection: Steam injection and flooding are very effective in recovering heavy viscous crudes. Thermal recovery is applicable for individual well stimulation or field-wide flooding. Incremental production cost is estimated at \$3 to \$6 per barrel.

In-situ Combustion: This process attempts to recover oil by burning a portion of in-place crude. Air or oxygen is injected to facilitate burning. The process is very complex involving multiphase flow of flue gases, volatile hydrocarbons, steam, hot water, and oil. Its performance in general has been insufficient to make it economically attractive to producers. Incremental production cost is estimated at \$5 to \$10 per barrel.

Gas-Miscible & -Immiscible Recovery

Miscible Gas Drive: In place of the costly hydrocarbon gases used in the past, miscible gas drives now inject such gases as carbon dioxide, nitrogen, or flue gas. Along with steam flooding, carbon dioxide flooding has proven to be among the most promising EOR methods for the U.S. because it takes advantage of plentiful, naturally-occurring carbon dioxide. Incremental production cost for carbon dioxide flooding is estimated at \$2 to \$8 per barrel.

Chemical Recovery

Polymer Flooding: In this enhanced waterflooding method, high molecular weight water-soluble polymers are added to the injection water to improve its mobility ratio, reducing oil “bypassing” and raising yields. Permeability profile modification treatments with polymer solutions are becoming increasingly common. Incremental production cost is estimated at \$5 to \$10 per barrel.

Surfactant Flooding: Also known as micellar-polymer flooding, low-tension waterflooding, and micro-emulsion flooding, this method typically involves injecting a small slug of surfactant solution into the reservoir, followed by polymer-thickened water, and then brine. Despite its very high displacement efficiency, micellar-polymer flooding is hampered by the high cost of chemicals and excessive chemical losses within the reservoir. Incremental production cost is estimated at \$8 to \$12 per barrel.

Microbial/Biochemical Recovery

This method takes advantage of microbial byproducts in the reservoir, such as carbon dioxide, methane, polymer, alcohol, acetone, and other compounds. These, in turn, can change oil properties in a positive direction, and thereby facilitate additional oil recovery. This method is usually applicable to marginal oil wells in the well stimulation mode. Incremental production cost is estimated at \$1 to \$8 per barrel.

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Main Program Areas

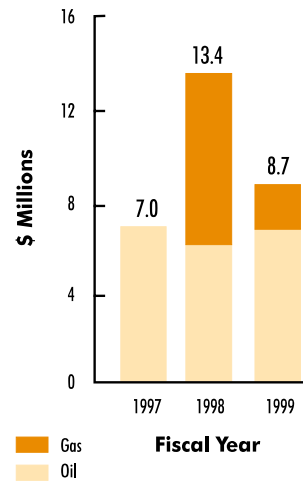
Reservoir Efficiency Processes Program comprises the following areas:

- Enhanced Oil Recovery
 - Thermal
 - Gas-miscible and -immiscible
 - Chemical
 - Microbial/Biochemical
- Natural Gas and Oil Technology Partnership (Oil and Gas Recovery Technology Forum)

The following pages highlight specific program accomplishments and suggest the range and variety of program activities.

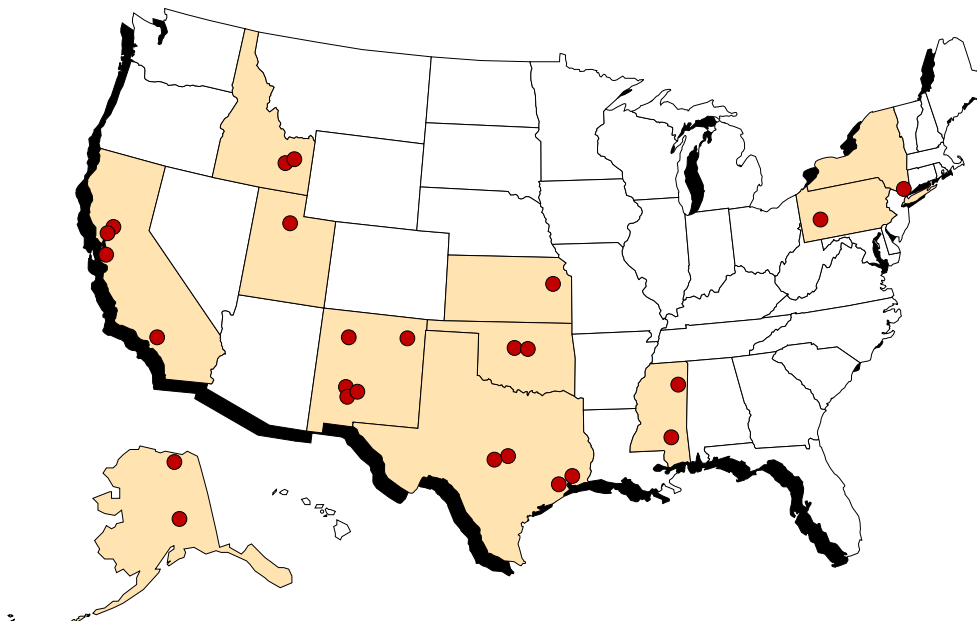
The program activities include research to develop and demonstrate tools and methodologies that permit oil operators to recover hydrocarbons from known reservoirs not producible by current technology. Activities also support university research in extraction technologies and recovery process modeling to ensure a supply of well-trained workers. The objective is to develop and transfer scientific breakthroughs, such as those by the National Laboratories, which are applicable to the industry and that benefit our economy and the environment.

Reservoir Efficiency Processes Program Budget



Project Sites

The Program currently involves 25 projects in 11 States.



Drivers

- Steadily increasing demand for transportation fuels and steadily declining domestic oil production place the Nation at an energy security risk. The Nation needs a reliable supply of oil and natural gas.
- Two-thirds of the oil and one-half of natural gas that has been discovered remain unrecoverable with today's technology. Much higher recovery efficiency is possible with improved technology.
- Rates of abandonment of oil and gas wells (15,000 to 22,000 per year) and offshore platforms (100 to 150 per year) are unacceptably high.
- Independent producers are assuming an increasing share of U.S. production activities, yet they do not have their own research capabilities, nor the means to assume the perceived risk to try advanced technologies used by majors.
- Technical problems are so complex that they require joint research involving producers, service companies, universities, and the National Laboratories.

Goals

- By 2010, make available new technologies and more efficient existing recovery processes that will stabilize domestic oil recovery.
- By 2005, increase the rate of enhanced oil production (as defined and tracked by the *Oil & Gas Journal*) by at least 10 percent.
- By 2005, stabilize the oil and gas well abandonment rate.
- By 2005, develop and field-test new approaches (other than those based on gel treatments) to reservoir permeability modification for higher waterflooding efficiency and other displacement processes.

Strategies

- Support ongoing fundamental and applied research in critical reservoir efficiency processes and process modeling.
- In partnership with industry, academia and National Laboratories, develop the scientific basis for major technology breakthroughs that are applicable to both oil and gas, and have potential for substantial increases in reservoir efficiency processes.
- Support research to develop new and less costly technologies, and prolong the lifetime of marginal wells and maturing oil fields.
- Expedite technology transfer to industry by conducting pilot-scale demonstrations of proven laboratory technologies, and by working with industry associations, such as the PTTC, to provide focused technology workshops, information resource centers, and computer-based information.

Reservoir Efficiency Processes Program

Measures of Success

- By the year 2005, stop overall decline in oil production, with application of advanced technologies in the field.
- By 2005, increase the percentage of U.S. oil production by enhanced oil recovery methods to at least 15 percent (currently 12 percent).
- By 2005, develop new approaches and software for reservoir modeling that is at least ten times faster than it is currently possible.
- By 2005, develop and field test a Virtual Company Concept for reservoir management.

Enhanced Oil Recovery Research and Development

Partnering with industry, DOE focuses on research and development of four improved oil recovery methods: thermal, gas-miscible, chemical, and microbial. By organizing research in these four areas, DOE can focus its efforts on those wells most threatened by premature abandonment and the resulting loss of significant oil reserves. DOE directs most of its support, which includes financial contributions, as well as personnel and unique facilities and expertise, to recovery technologies that have the

highest potential for increased oil and gas production.

A total of 26 discrete research projects now are underway in the EOR area of the Reservoir Efficiency Processes Program. This area is oriented to basic and applied research, which is typically conducted by universities and National Laboratories. The projects highlighted herein are representative of the supporting research needed to build a solid technology foundation on which the other program areas can build. Some of the projects in this area described below:

A thermal recovery project at West Hackberry, Louisiana, is demonstrating the improved oil recovery potential of air injection for many oil reservoirs throughout the U.S. Gulf Coast. Amoco (now called "BP Amoco") is currently field testing whether air injection can be combined with the double displacement process, which is gas displacement of a water-invaded column to generate tertiary oil recovery through gravity drainage. Louisiana State University also participates in the project by providing independent study and technology transfer.

The project goal is to create a new EOR process for light oil reservoirs that would be profitable in today's economic environment.

Success Stories

Field Testing of Microbial Recovery

Research on the use of microbes in low producing oil wells was applied in two extensive field tests recently completed in Oklahoma. Tests demonstrated 13 and 20 percent improvements in the oil recovery rate. Based on these results, negotiations were completed for licensing the technology to a private company, and issuance of a license is pending. The laboratory work has also led to the development of a permeability modification technology and a patent application in that area.

Permeability Modification Control

Six wells in Prudhoe Bay, Alaska, were treated with chemical gels. After treatment, the total yield of oil per day for the wells increased, while the total production of salt water decreased by 19,000 barrels per day.

A key aspect of the process is the selection of target reservoirs that possess sufficient reservoir temperature to consume oxygen through spontaneous in-situ combustion. Without in-situ combustion, unreacted oxygen in the produced gas could lead to emulsions, corrosion, and, in large enough concentrations, explosions in the production equipment. While air injection has been accepted for heavy oil reservoirs, the West Hackberry project is the first in the Gulf Coast to use air injection successfully in a high-permeability, light-oil reservoir.

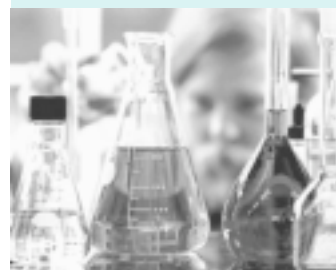
Two reservoirs are currently undergoing air injection, which can be less costly than carbon dioxide injection, and can be used in areas where carbon dioxide is not available. The first reservoir already has more than doubled its oil production rate from 180 to 370 barrels per day. A similar increase is expected in the additional reservoirs within the oil field. The project is expected to yield over 3 million barrels of incremental oil.

New Mexico Institute of Mining and Technology and Stanford University are conducting laboratory and field-based research to better understand physical phenomena associated with miscible

and immiscible gas displacement, especially carbon dioxide. Of the available suite of advanced oil recovery methods, gas injection presently has the greatest potential for additional oil recovery from U.S. light oil reservoirs. Gas injection, particularly miscible or near-miscible flooding, has been applied to relatively homogeneous reservoirs.

Efforts are aimed at further exploration of the applicability of selective mobility reduction in the use of foam flooding; improving the effectiveness of carbon dioxide flooding in heterogeneous reservoirs; demonstrating how gas injection can be applied to heterogeneous reservoirs; and investigating new concepts that can be applied by field operators within the next two to five years. New concepts that are being considered have the potential of recovering oil believed to be unrecoverable.

To date, New Mexico Tech research has shown good results for low permeability reservoirs, such as the Permian basin Sprayberry, which has more than 6 billion barrels of remaining oil. Several oil companies have acquired Stanford University's new super-high-speed computing techniques that significantly reduce cost of reservoir simulation.



Lawrence Berkeley National Laboratory (LBNL) is investigating effective surfactant packages and a mechanism-based simulator of foam displacement in porous media for mobility control in improved oil recovery processes. Although modern improved oil recovery practice is well developed in the area of dislodging trapped oil, mobility control is not well-developed, even though the basic principles are understood. Because reservoirs are naturally heterogeneous, all current enhanced oil recovery processes (including steam flooding, hydrocarbon injection, carbon dioxide flooding, alkaline flooding, and surfactant flooding) require mobility control.

This work focuses on the use of gas-aqueous surfactant dispersions as a general mobility control agent, both in establishing macroscopic sweep efficiency and microscopic displacement efficiency, and are under development for a range of enhanced oil recovery processes. Foams are under development for both in-depth sweep improvement and local well profile modification.

Idaho National Engineering and Environmental Laboratory (INEEL) is currently developing and field testing improved, more cost effective, and environmentally acceptable methods of oil recovery using microbial enhanced oil recovery (MEOR) technology. This research involves production and

Success Story

One-Dimensional Reservoir Simulation

Researchers at the Department of Petroleum Engineering at Stanford University, funded by DOE and a consortium of oil companies, have developed a novel computational technique that greatly improves current state-of-the-art reservoir simulation technology. Basically, fluid flow in a reservoir is calculated in one dimension, but also separately along many "streamlines." This one-dimensional simulation technology is 1,000 times faster than conventional reservoir simulation, and is more accurate as well (even for very complex production scenarios). Such accelerations in the time needed to complete simulations will allow a much more extensive search for optimal production strategies.

application of microbially produced polymers and biosurfactants produced from agricultural wastes; elucidation and quantification of microbial mechanisms responsible for oil displacements; and development of microbial systems for oil recovery and application of MEOR systems in industry cost-shared field demonstrations. MEOR research has progressed rapidly in the past few years, but improved understanding of the controlling mechanisms and economics of MEOR processes are required before this technology will be a viable method for general application.

Natural Gas and Oil Technology Partnership

The Natural Gas and Oil Technology Partnership provides a mechanism for the petroleum industry to collaborate with DOE's National Laboratories on near-term RD&D efforts to improve exploration and recovery of oil and gas. Through the Partnership, industry gains access to unique capabilities of the Laboratories in such areas as electronics, instrumentation, materials, computer hardware and software, engineering, systems analysis, physics, and expert systems.

The Partnership consists of four independently run forums: Oil and Gas Recovery Technology; Diagnostics & Imaging Technology; Drilling, Completion, and Stimulation Technology; and Environmental Technology (includes oil refining). The Partnership stimulates, facilitates, and coordinates



the development and rapid transfer of technology to industry. The program is industry-driven and leveraged by matching contributions.

DOE's National Laboratories have developed cutting edge expertise in advanced computing for national defense. Now, through the Natural Gas and Oil Technology Partnership, this expertise is helping to maintain the technology leadership of the U.S. petroleum industry. Massively Parallel Computing and Internet technologies, for instance, promise to revolutionize industry practices in oil and gas discovery and recovery.

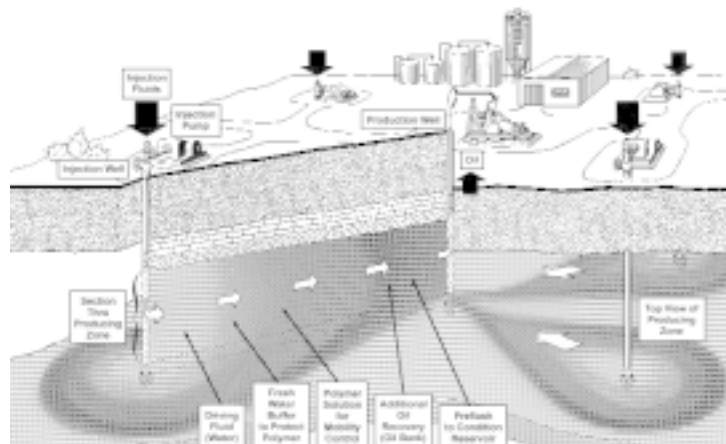
Through the Partnership, oil and gas data of public record is being made more accessible to hundreds of small independent producers. Over 20 oil- and gas-producing States have asked to join the initial participants, Texas and California, in creating a standardized data interface

that will be accessible via the Internet.

CHEMICAL (POLYMER)

FLOODING

The method shown requires a preflush to condition the reservoir, the injection of a polymer solution for mobility control to minimize channeling, and a driving fluid (water) to move polymer solution and resulting oil bank to production wells.



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The Oil and Gas Recovery Technology Forum directs 14 selected cost-shared projects that aim to improve production from existing oil and gas wells by expediting the development and transfer of recovery technologies:

Note: Numbers in parenthesis indicate the number of participating entities.

- Applied production technology (10);
- Extending borehole electromagnetic imaging of cased wells (8);
- Fluid injection into tight rocks (7);
- Fracture mapping and slimhole geophone array (2);
- Improved prediction of multiphase flow in petroleum reservoirs (5);
- Reduction of well failures in diatomite (12);
- Optimizing reservoir production (5);
- Wireless telemetry tool (2);

- Improved waterflooding through control of brine composition and other factors (3);
- Innovating gridding and solution techniques for

Success Story

Supporting Software, Handbooks, and Manuals for Independent Producers

ONGPT has made available 21 user-friendly software packages, designed to help independent producers recover more from mature oil fields, for downloading directly from the Internet. These are free of charge and all software runs on personal computers. Popular software packages include the so-called "simplified predictive models" for EOR technologies. By predicting the performance of steam flooding, in-situ combustion, polymer flooding, carbon dioxide flooding, and chemical flooding, this software provides a simple, inexpensive way to identify the technology most suitable or economic for a given oil property. The predictive models can be reviewed and downloaded from:

<http://www.npto.doe.gov/software/softindx.html>

DRILLING &
COMPLETION

DIAGNOSTICS
& IMAGING

RESERVOIR
EFFICIENCY

RESERVOIR
LIFE

GAS
STORAGE

ENVIRON-
MENTAL

OIL
PROCESSING

GAS
PROCESSING

MODELING &
ANALYSIS

- high performance reservoir simulation (4);
- Development of a new generation of petroleum reservoir simulator (13);
- Fluid identification acoustic logging tool (14);
- High-resolution reservoir characterization, using seismic well and dynamic data (6); and
- Optimization of pyrolysis and aqueous pyrolysis of heavy oil from California (9).

Improving the yield of marginal wells, making them economically-sound for longer periods to discourage premature abandonment, does not always require application of the most sophisticated reservoir life extension technologies. Sucker rod failures, inability to measure oil properties in the field, or paraffin build-up – any one of these problems – can sway economic pressures toward abandonment. By providing independent producers with immediate, cost-effective, and realistic solutions to these and other problems, the Oil and Gas Recovery Technology Forum is helping to "buy time" for producers and to extend the life of marginal wells.

The Oil and Gas Recovery Technology Forum partnerships are characterized by industry-driven technology transfer, flexible cost-sharing agreements, short proposals, and short response times. Industry partners include independent and major oil and gas producers as well as service companies.

The participants of the Forum comprise 23 exploration and production companies, 22 service companies, four universities, and eight National Laboratories.

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